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Abstract

Airborne separation assurance is a key requirement for Free Flight operations. This paper investigates the feasibility of airborne separation assurance for free flight by evaluating the performance of Conflict Detection and Resolution (CD&R) schemes in a simulated air traffic environment. Two qualitatively different CD&R methods were utilized; one based on a geometric optimization approach, and the other based on a modified potential-field approach. Both CD&R methods were evaluated in an air traffic simulation environment provided by the Future ATM Concepts Evaluation Tool (FACET). The evaluation was based on a realistic free flight traffic scenario constructed with initial conditions from actual air traffic data; approximately 1,000 aircraft were represented in this 6-hour air traffic scenario. Three metrics were utilized for the performance evaluation: safety, efficiency and stability. The results of the performance evaluation data indicate that airborne separation assurance performed quite well in the Free Flight evaluations: (1) All of the conflicts were resolved; (2) The impact on flight efficiency, as measured by path-length and flight-time changes, was small; and, (3) The impact on system stability, as measured by additional trajectory deviations due to the "domino effect," was low to moderate (depending on the CD&R method used).

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Introduction

In the Distributed Air-Ground Traffic Management (DAG-TM) paradigm of operations,[1,2] the ground-based Air Traffic Service Provider may, under certain operational conditions, delegate separation responsibility to the flight deck crews of appropriately equipped aircraft. Airborne conflict detection and resolution (CD&R) capability is therefore a key requirement for this "free maneuvering" aspect of DAG-TM.

The primary objective of this research effort is to study the feasibility of airborne separation assurance for free flight by evaluating the performance of aircraft-based CD&R in a simulated air traffic environment. A secondary objective is to explore techniques for assessing the viability and relative merits of CD&R algorithms. The performance metrics developed for performance evaluation can also be utilized for the refinement of CD&R algorithms prior to their formal assessment and comparison for a selection process.

Two qualitatively different CD&R methods were used in this study; one is based on a geometric optimization approach,[3] and the other is based on a modified potential-field approach.[4,5] These CD&R methods were used to provide airborne self-separation in a simulation environment provided by the Future ATM Concepts Evaluation Tool (FACET),[6] using a realistic free flight traffic scenario constructed with initial conditions from actual air traffic data. An attempt was made to identify any quantitative and qualitative differences between the performance of these two methods. The purpose of this comparison was not to pick a "winner" but to investigate the performance of qualitatively different CD&R algorithms under ideal free flight conditions, and identify any characteristic features of the two approaches.

It is assumed that each aircraft broadcasts its current states (components of position and velocity) via datalink, and that perfect state information is available to all other aircraft within broadcast range. Only level-flight conflicts and horizontal-plane resolution maneuvers (airspeed and/or heading changes) were considered in this initial study.

A brief description of the air traffic simulation environment used for the performance evaluation is presented in the next section; the following section provides an overview of the two CD&R methods utilized in this study. The construction of a realistic free flight traffic scenario is then described. Finally, the performance metrics and results for the two airborne self-separation methods are presented. The paper closes with some concluding remarks.

Air Traffic Simulation Environment

The performance evaluation of airborne self-separation for free flight was conducted in an air traffic simulation environment known as the Future ATM Concepts Evaluation Tool (FACET). A detailed description is given in Ref. 6; this section provides an overview.

The purpose of FACET is to provide a simulation environment for exploration, development and evaluation of advanced Air Traffic Management concepts. Examples of these concepts include new Air Traffic Management paradigms such as Distributed Air/Ground Traffic Management, advanced Traffic Flow Management, and new Decision Support Tools for controllers working within the operational procedures of the existing air traffic control system. FACET models system-wide en route airspace operations over the contiguous United States. The architecture of FACET strikes an appropriate balance between flexibility and fidelity. This feature enables FACET to model airspace operations at the U.S. national level, and process over 5,000 aircraft on a single desktop computer running on any of a wide variety of operating systems. FACET has been designed with a modular software architecture to facilitate rapid prototyping of diverse Air Traffic Management concepts. FACET has prototypes of several advanced Air Traffic Management concepts: airborne self-separation; a Decision Support Tool for direct routing; advanced Traffic Flow Management techniques utilizing dynamic density predictions for airspace redesign and aircraft rerouting; and, the integration of space launch vehicle operations into the U.S. National Airspace System.

CD&R Methods

Numerous methods, based on a variety of approaches, are available for aircraft conflict detection and resolution.[7] Implementations of two CD&R methods, based on qualitatively different approaches, are available in FACET. Both methods resolve conflicts utilizing information on current positions and velocity vectors only. A brief description of these methods is given below.

Geometric Optimization CD&R Method
An overview of the Geometric Optimization approach to CD&R is presented here; a detailed description is given in Ref. 3. This approach utilizes the geometric characteristics of aircraft trajectories, along with intuitive reasoning, to obtain closed-form analytical expressions for optimal combinations of heading and speed commands for conflict resolution in the horizontal plane. The conflict resolution is optimal in the sense that it minimizes the velocity vector changes required for each aircraft. It can be shown that this results in minimum deviations from the nominal trajectories (subject to certain simplifying assumptions). Trajectory deviations for conflict resolution are shared equally by the aircraft involved in the conflict. Although CD&R functions are performed at each update cycle, application of the geometric optimization solution to a two-aircraft conflict should result in a single discrete trajectory modification by each aircraft to avoid the conflict. For two-aircraft conflicts, the optimality of these simple analytical solutions has been validated by comparison with numerical solutions from a compute-intensive optimization process utilizing a Positive Semi-Definite Programming approach. Multiple-aircraft conflicts are resolved sequentially, with each aircraft resolving its most immediate conflict at each update cycle. After the current conflict is resolved (positive range-rate), and a conflict-free recovery trajectory becomes available (over the specified look-ahead time), each aircraft resumes its nominal airspeed and flies a course to its destination.

Modified Potential-Field CD&R Method

An overview of the Modified Potential-Field approach to CD&R is presented here; a detailed description is given in Refs. 4 and 5. This method resolves aircraft conflicts by emulating the basic attraction and repulsion features of charged particles in a potential field. At each time step, a new velocity vector is constructed by adding incremental velocity vectors for conflict resolution to a nominal velocity vector that returns the aircraft to its destination at its nominal airspeed. This yields a combination of airspeed and heading commands for conflict resolution in the horizontal plane. During conflict resolution, each aircraft adjusts its trajectory under the assumption that the other aircraft will not change its current trajectory; at the next update cycle, it reacts to any trajectory changes made by the other aircraft. Consequently, the aircraft velocity vector is generally modified at each update cycle, resulting in continuous trajectory changes. In a multiple conflict situation, each aircraft determines a velocity vector change that attempts to simultaneously resolve all conflicts by vector summation of individual solutions for all conflicts.

Free Flight Traffic Scenario

A realistic free flight traffic scenario was constructed, using initial conditions from actual air traffic data. A 24-hour data file from the Enhanced Traffic Management System (ETMS) was recorded for air traffic over the United States on March 18, 1999. From this data file, a subset of traffic data was extracted for the Denver Air Route Traffic Control Center (ARTCC), corresponding to 1,058 flights that operated in Denver ARTCC during the 3-hour period from 9 a.m. to 12 noon (Denver time). The times and positions corresponding to each aircraft's first appearance in Denver ARTCC airspace (Fig. 1) were determined; they are referred to as birth points. The birth points provide initial conditions for simulating great circle trajectories that "fly" the aircraft directly to their destinations. The resulting traffic scenario provides a realistic representation of free flight operations (under the simplifying assumption of a constant wind field).

Only level-flight conflicts and horizontal-plane resolution maneuvers (heading and speed changes) were considered in this initial study. The modeling of climbs and descents in the simulation environment (FACET) was therefore disabled for this study. Consequently, all aircraft were "born" in the simulation at their maximum (cruise) altitude as recorded in the ETMS data set. In order to restrict the scope of the CD&R evaluation to free flight operations in Class A airspace, only aircraft with maximum recorded altitudes at or above FL180 were considered for inclusion in the free flight traffic scenario; there were 972 such aircraft present in the 3-hour Denver ARTCC data set described above. In an effort to reduce simulation run times, 5 flights that flew to very distant destinations (e.g., Tokyo, Japan) were removed from the scenario.

Fig. 1: Denver ARTCC Airspace

FACET was used (without any CD&R) to generate a preliminary set of great circle level-flight trajectories, along with a list of observed conflicts. It was found that 12 aircraft were "born" in conflict with other aircraft that had already entered the simulation at earlier times; e.g., an aircraft departing from Denver International Airport (DIA) may be "born" in conflict with an aircraft flying over DIA. These 12 aircraft were removed from the scenario. The final number of aircraft included in the free flight traffic scenario was 955, corresponding to over 98% of the original 972 aircraft found in Class A airspace.

Using FACET, great circle trajectories were generated (without any CD&R) for the 955 aircraft described above. This traffic scenario, run without any CD&R, is referred to as the reference free flight traffic scenario.

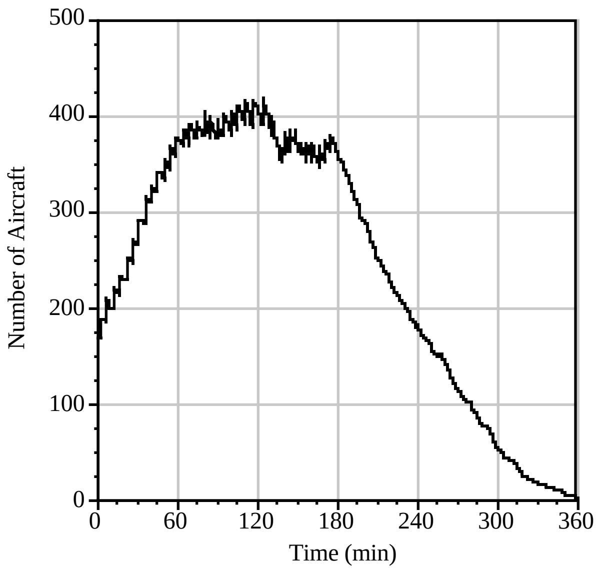

Fig. 2a: Time History of Aircraft Count

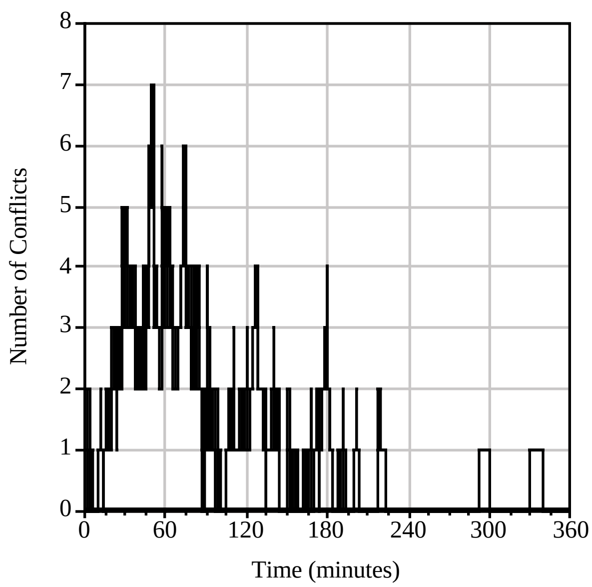

Fig. 2b: Time History of Conflict Count

Fig. 2a shows the total number of aircraft as a function of time, over the duration of the reference free flight traffic scenario. The scenario begins at about 9 a.m. (Denver time) with 172 aircraft; new aircraft enter the simulation at their appropriate birth times between 9 am and 12 noon (Denver time). Aircraft leave the simulation when they arrive at their destination. The last aircraft in the simulation lands at its destination approximately 6 hours after the simulation start time. It is noted that the peak traffic count of 422 aircraft occurs at approximately 11 am (Denver time).

Fig. 2b shows the conflict count as a function of time, over the duration of the reference free flight traffic scenario. A pair of aircraft are in conflict if they have a horizontal separation of less than 5 nm and a vertical separation of less than 1000/2000 ft below/above FL 290 respectively. It was determined that there were a total of 129 conflicts, involving 209 aircraft (many of which had more than one conflict during their flight), over the entire 6-hour duration of the reference free flight traffic scenario.

In order to evaluate the performance of airborne self-separation for free flight, FACET was again used to simulate trajectories (for all of the 955 aircraft in the scenario) from the birth points to the corresponding destinations, with each of the two CD&R methods engaged. The nominal trajectories are direct (great-circle) routes to the destination at the nominal airspeed; aircraft deviate from their nominal trajectories (heading and speed changes) only to resolve conflicts. For this initial study on free flight feasibility, perfect state information was assumed for CD&R, and turn/acceleration dynamics were disabled in the FACET simulation environment. After conflict resolution, an aircraft resumes a course to its destination at its nominal airspeed. Aircraft are removed from the simulation when the distance to destination drops below a small value (0.14 nm) derived from the simulation's integration time-step of 1 second and a maximum airspeed of 500 knots. The CD&R function is suppressed for conflicts involving an aircraft that is within the terminal area of its destination airport. This eliminates problems associated with several aircraft trying to arrive at the same destination at roughly the same time in the simulation; in the real world, this problem is averted by arrival metering and/or controller actions. For the purposes of this study, the terminal area is modeled as a circular zone, centered at the airport location, with a radius equal to 50 nm.

Although the two CD&R methods used in this study are qualitatively different, an attempt was made to implement their algorithms under a uniform set of guidelines, defined as follows. A subject aircraft evaluates all aircraft within a circular surveillance zone of radius 125 nm. It is noted that in a horizontal flight scenario, aircraft that are separated vertically from the subject aircraft by at least 1000/2000 ft below/above FL290 can not get into a conflict. Conflict detection is based on a horizontal separation standard of 5 nm, with a conflict look-ahead time of 8 minutes; i.e., a conflict is declared only if the minimum horizontal separation is predicted to drop below 5 nm within the next 8 minutes. Each CD&R scheme uses its logic to determine a new velocity vector (speed and heading combination) for conflict resolution. The range of valid airspeeds for each aircraft is bounded by its performance (stall/buffet and maximum Mach) limits. For each aircraft in the simulation, the lower airspeed limit was set to 85% of its cruise speed, and the upper airspeed limit was set to 110% of its cruise speed. If the desired airspeed for conflict resolution lies outside the aircraft's performance limits, it is set equal to the appropriate (upper or lower) limit, and the heading angle is adjusted to compensate (so that the conflict can still be resolved). Since this initial study assumes perfect knowledge of aircraft states, a conflict resolution buffer is not necessary (a small 0.1 nm buffer was added to provide numerical stability for the Geometric Optimization method). Hence, conflict resolution maneuvers for both CD&R methods attempt to provide a horizontal separation of 5.1 nm.

Performance Metrics and Results

The primary objective of this study is to evaluate the feasibility of airborne separation assurance for free flight, and to evaluate its overall impact on air traffic operations. The free flight traffic scenario (described in the previous section) was run with Geometric Optimization CD&R enabled, and again with Modified Potential-Field CD&R enabled. The resulting free flight trajectory sets (with CD&R) were each compared against the reference free flight trajectory set (no CD&R), using the following performance metrics:

(1) Safety, (2) Efficiency, and, (3) Stability.

Safety

This metric records the extent to which separation was maintained during operations with a CD&R scheme engaged. There was no observed loss of separation in the Free Flight simulations; both the geometric optimization CD&R method and the modified potential-field CD&R method resolved all of the 129 conflicts found in the reference set.

The process of resolving a current conflict may create additional conflicts in the future. Although both the Geometric Optimization and Modified Potential-Field CD&R methods created such conflicts (discussed later in the sub-section on Stability), all of these additional conflicts were also resolved.

Efficiency

The Direct Operating Cost (or DOC) of a flight is a function of time and fuel, given by

$$DOC = C_t\ T + C_f\ W_f \tag{1}$$

where C_t (\$/hr) and C_f (\$/lb) represent the costs of time and fuel respectively, T is the flight time, and W_f is the weight of fuel consumed.

The efficiency of conflict resolution can be measured as the incremental Direct Operating Cost (ΔDOC) relative to the DOC of the reference trajectory.

$$\Delta DOC = C_t\ \Delta T + C_f\ \Delta W_f \tag{2}$$

In general, the incremental fuel consumption ΔW_f is a function of both the incremental flight-time ΔT and the incremental path-length $\Delta \ell$. Hence

$$\Delta DOC = fn(\Delta T, \Delta \ell) \tag{3}$$

The function in Eq. (3) above is complex, and depends on the aero-propulsive characteristics of the aircraft. For the sake of simplicity, this study uses the incremental flight-time ΔT and the incremental path-length $\Delta \ell$ instead of ΔDOC. Let $T_{reference}$ and $\ell_{reference}$ be the flight-time and path-length of a reference (no CD&R) trajectory, and let T_{CDR} and ℓ_{CDR} be the flight-time and path-length of a trajectory with a CD&R scheme engaged. The incremental path-length and flight time changes are then given by:

$$\Delta T = T_{CDR} - T_{reference} \quad (4)$$

$$\Delta \ell = \ell_{CDR} - \ell_{reference} \quad (5)$$

Each of the two free flight trajectory sets with CD&R engaged were compared against the reference free flight trajectory set (no CD&R). Data on flight-time changes (ΔT) and path-length changes ($\Delta \ell$) were then compiled.

Fig. 3 shows the distributions of flight-time changes for the Geometric Optimization CD&R method and the Modified Potential-Field CD&R method. Since the integration time-step used in the simulation was 1 sec, a cut-off threshold of ±2 sec was utilized for analysis of ΔT data. It is noted that over 98% of the flight-time changes are within ± 30 sec. One may conclude that flight-time changes due to airborne self-separation are small, relative to the average nominal flight time (birth point to destination) of approximately 92 minutes.

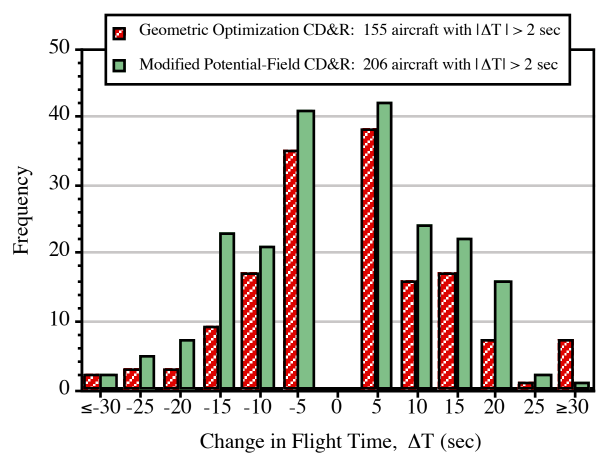

Fig. 3: Changes in Flight Time

Table 1 presents statistical parameters derived from the ΔT data shown in Fig. 3. The sample size (count of aircraft with $|\Delta T|$ > 2 sec) is 155 for Geometric Optimization CD&R, compared to 206 for Modified Potential-Field CD&R; implications of this difference are discussed later in this sub-section and in the sub-section on Stability. The signed mean (i.e., the mean of ΔT data) is small for both CD&R methods, with a value of 2 sec for Modified Potential-Field CD&R and 6 sec for Geometric Optimization CD&R. This is reflected in the near-symmetric distributions of ΔT evident in Fig. 3, indicating that the number of aircraft with early arrivals was roughly equal to the number of aircraft with late arrivals. The signed value of ΔT is not necessarily indicative of ΔDOC because although an early arrival decreases the time cost, the corresponding increase in speed generally increases the fuel cost. Therefore, the absolute mean (i.e., mean of $|\Delta T|$ data) was computed. It can be seen from Table 1 that the value for Geometric Optimization CD&R is 12 sec, and the value for Modified Potential-Field CD&R is 11 sec (about 8% lower). Table 1 also presents the absolute sum of flight-time changes (i.e., $\sum|\Delta T|$); this quantity may be regarded as a "system-level" efficiency metric that is indicative of the total system-wide costs of flight-time changes associated with conflict resolution. The values of this metric are 1810 sec for Geometric Optimization CD&R and 2226 sec for Modified Potential-Field CD&R. Compared with Geometric Optimization CD&R, the absolute sum for Modified Potential-Field CD&R is about 23% higher, even though the absolute mean is 8% smaller. The reason can be traced to the difference in the size of the data samples mentioned above (206 aircraft for Modified Potential-Field CD&R vs. 155 aircraft for Geometric Optimization CD&R). In other words, the system-wide effect of absolute flight-time changes is higher for Modified Potential-Field CD&R, but it is distributed over more aircraft, resulting in a lower absolute mean.

		Geometric Optimization CD&R Method	**Modified Potential-Field CD&R Method**
ΔT	Count for $\lvert\Delta T\rvert > 2$ sec	155 aircraft	206 aircraft
	Sgn. Mean	6	2
	Abs. Mean	12 sec	11 sec
	Abs. Sum	1810 sec	2226 sec
$\Delta \ell$	Count for $\Delta \ell > 0.2$ nm	5 aircraft	2 aircraft
	Mean	0.91 nm	0.25 nm
	Sum	4.6 nm	0.50 nm

Table 1: Results of Efficiency Analysis

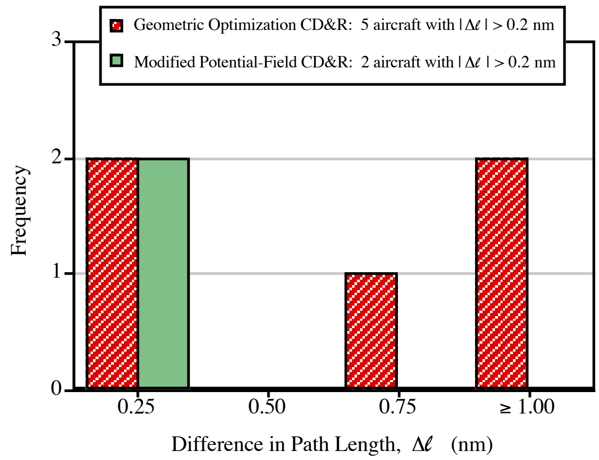

Fig. 4: Changes in Path Length

Fig. 4 shows the distributions of path-length changes for the Geometric Optimization CD&R method and the Modified Potential-Field CD&R method. It is evident that these distributions have a very small sample size. Even though a large number (~100's) of aircraft experienced path-length changes, most of them were not measurable because they were smaller than the uncertainty in path-length measurements. This uncertainty arises from the distance-to-destination threshold of 0.14 nm used to drop an aircraft from the simulation. For this reason, a cut-off value of 0.2 nm was established for utilizing data on path-length changes. Only a few aircraft experienced path-length changes above this threshold (see Fig. 4). It is noted that even the maximum change in path-length (about 2.3 nm) is very small, relative to the average nominal path length (birth point to destination) of approximately 664 nm.

The statistically insignificant size of the data samples notwithstanding, the mean values of $\Delta\ell$ for the two CD&R methods are given in Table 1 for completeness. It also gives the sum of path-length changes (i.e., $\sum \Delta\ell$); this is a "system-level" metric that is indicative of the total system-wide costs of path-length changes associated with conflict resolution. It can be seen that the values of both the mean and sum are smaller for the Modified Potential-Field CD&R method compared to the Geometric Optimization CD&R method.

As stated earlier in this sub-section, the efficiency metric is a composite of ΔT and $\Delta\ell$. One possible approach to combining these two quantities is to express $\Delta\ell$ in terms of an equivalent ΔT. At a typical speed of about 450 knots, 1 nm corresponds to roughly 8 sec. Using this "conversion factor" it is clear from the data presented in Table 1 that, for both CD&R methods used in this study, the contribution of $\Delta\ell$ to the efficiency metric is at least an order of magnitude lower than the contribution of ΔT. For the purposes of this study, the absolute sum of ΔT will be regarded as a proxy for system-level efficiency (or cost of conflict resolution).

Stability

A major research issue associated with the airborne self-separation concept is whether the decentralization of separation responsibility could "destabilize" the traffic flow.[8,9] In the current mode of operations where a ground-based controller is responsible for traffic separation, the traffic flow is generally stable due to the centralization of control authority. The central controller performs CD&R by issuing coordinated solutions to solve separation problems among all aircraft in his/her control. It may be argued that in the current system of air traffic operations, a "centralized" human controller resolves conflicts by utilizing a "system-level" performance index oriented towards maintaining a stable (i.e., orderly) flow of traffic. However, the resulting deviations may not be user-preferred for individual aircraft, resulting in inefficient trajectories that can adversely affect the aggregate efficiency of the entire system. Studies on distributed and centralized control strategies for conflict resolution can be found in Refs. 10 and 11.

Airborne self-separation gives individual users the freedom to redesign their own trajectories for conflict resolution. In this distributed control paradigm of operations, each aircraft performs CD&R at an individual level, utilizing an "aircraft-level" performance index oriented towards efficient resolution of its own conflict. It can be seen from the results of the previous sub-section that the trajectory deviations are indeed quite small for both of the qualitatively different CD&R methods. The issue is whether this efficiency comes at the price of reduced system stability. In the process of efficiently resolving its current conflict, an aircraft may create new conflicts with neighboring aircraft flying along conflict-free trajectories, which in turn may create new conflicts during their own conflict resolutions. This propagation of conflicts is sometimes referred to as the "domino effect."

One possible measure of the domino effect is the incremental number of aircraft that get drawn into conflicts by other aircraft that are trying to resolve their own conflicts. In a given traffic scenario, let A_{nom} represent the set of aircraft that have conflicts if they fly their reference trajectories without performing any CD&R functions. Let A_{CDR} represent the set of aircraft in the same traffic scenario that experience trajectory deviations in the process of resolving all predicted conflicts (assuming perfect CD&R systems). Consider the intersection of these two sets as shown in Fig. 5. The destabilizing effect caused by the conflict resolution process manifests itself through aircraft that experience deviations during CD&R operations even though they did not have conflicts in their reference trajectories. This is represented by a set (D) of aircraft that were drawn into conflicts by other aircraft in the process of resolving their own conflicts. In general, there will also be a small set (S) of aircraft that had conflicts in their nominal trajectories, but did not experience deviations during CD&R operations due to the prior actions of other aircraft resolving their own conflicts. This represents a stabilizing effect caused by the conflict resolution process. The net effect of conflict resolution on traffic flow stability can be characterized by a Domino Effect Parameter (DEP) defined as:

$$DEP = \left[\left(\frac{D}{A_{nom}} \right) - \left(\frac{S}{A_{nom}} \right) \right] = \left(\frac{D - S}{A_{nom}} \right) \tag{6a}$$

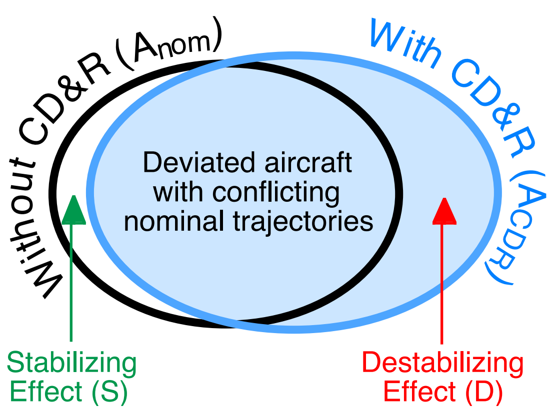

Fig. 5: Definition of Stability Analysis Parameters

	Geometric Optimization CD&R Method	**Modified Potential-Field CD&R Method**
A_{nom}	209	209
A_{CDR}	248	352
D	47	145
S	8	2
$\boldsymbol{DEP}$	**0.19**	**0.68**

Table 2: Results of Stability Analysis

From the structure of Fig. 5, it can be easily shown that an equivalent expression for the Domino Effect Parameter is given by

$$DEP = \left(\frac{A_{CDR}}{A_{nom}} - 1 \right) \tag{6b}$$

The stability analysis described above was conducted for both the Geometric Optimization and Modified Potential-Field CD&R methods. The results are presented in Table 2. It can be seen that Modified Potential-Field CD&R affects the trajectories of many more aircraft than Geometric Optimization CD&R, resulting in a significantly higher value of the Domino Effect Parameter. However, it is important to note that while Modified Potential-Field CD&R causes the deviations of 42% more aircraft than Geometric Optimization CD&R, the corresponding increase in system-wide conflict resolution cost is of the order of 20%.

It is conjectured that the sharp difference in domino effect between the two CD&R methods arises from a qualitative difference in their conflict resolution methodologies. In the Geometric Optimization CD&R method each aircraft resolves only the most immediate conflict within the specified look-ahead time, whereas in the Modified Potential-Field CD&R method each aircraft simultaneously resolves all conflicts predicted to occur within the specified look-ahead time.

It is emphasized that the mere existence of a domino effect does not necessarily result in a situation where conflicts cannot be resolved. In fact, both CD&R methods successfully resolved all conflicts (including those arising from the domino effect), as reported in the sub-section on Safety.

However, a substantial domino effect can degrade the aggregate efficiency of the system. This is reflected in the results presented in the sub-section on efficiency where it was reported that Modified Potential-Field CD&R yields a higher system-wide conflict resolution cost.

Conclusion

The feasibility of airborne separation assurance for free flight was investigated by evaluating the performance of aircraft-based CD&R in a simulated air traffic environment. A realistic free flight traffic scenario, constructed with initial conditions obtained from actual air traffic data, was utilized in this study.

Three metrics were developed for the performance evaluations: safety, efficiency, and stability. Results were generated using two qualitatively different CD&R methods: one based on a geometric optimization approach, and the other based on a modified potential-field approach. Both CD&R methods successfully resolved all conflicts. They also provided very efficient conflict resolutions, as evidenced by small trajectory deviations measured in terms of path-length changes and flight-time changes. There were some quantitative as well as qualitative differences between the efficiency results for the two methods. A domino effect was observed for both CD&R methods; its magnitude may be tentatively characterized as "low" for Geometric Optimization CD&R, and "moderate" for Modified Potential-Field CD&R. This difference is believed to arise from a qualitative difference in the conflict resolution methodologies of the two CD&R methods. Overall, the performance evaluation supports the feasibility of airborne self-separation for free flight operations.

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